# CHAPTER 3. Models for the origin of Himalayan inverted metamorphism and magmatism.

## 3.1. Introduction

Scientists studying the geologic evolution of the Himalayan generally assume that orogeny began in the Late Cretaceous-Early Eocene when India first collided with Asia (e.g., Le Fort, 1996; Rowley, 1996; Yin and Harrison, 2000). It has also been a general point of agreement that convergence across the Himalaya shifted progressively towards the foreland as mountain building progressed. The Main Central Thrust (MCT) is thought by many to have formed south of the Indus Tsangpo suture during the Miocene (e.g., Hodges et al., 1996). South of the MCT, Late Miocene movement occurred along the Main Boundary Thrust (MBT) (e.g., Meigs et al., 1995) and the Main Frontal Thrust (MFT) is presently active (e.g., Yeats et al., 1992). Thus during the development of the Himalayan range, slip is assumed to have been primarily accommodated by the thrust closest to the Indian foreland (e.g., Seeber and Gornitz, 1983).

Building on this foundation, some researchers proposed that Himalayan inverted metamorphism developed during MCT slip (e.g., Le Fort, 1975; England and Molnar, 1993), whereas others suggested that recrystallization of the footwall units occurred prior to their juxtaposition with the hanging wall (e.g., Searle and Rex, 1989; Hubbard, 1996). The origin of leucogranite magmas found in structurally higher levels of the Greater Himalayan Crystallines have also been linked to slip along the MCT (Le Fort, 1975; England et al., 1992) or South Tibetan Detachment System (STDS) (Harris et al., 1993; Harris and Massey, 1994).

In this chapter, we classify the numerous models that have been proposed to explain the evolution of the MCT into two broad categories. The first class of models are purely concerned with a description of the history of motion that brought the range from one state to another (i.e., kinematic models). Models in the second category permit interpretation of observations in terms of material forces and are constrained by parameters including geometry, physical conditions, temporal constraints, and mechanical properties. Several models developed to explain the evolution of the MCT call upon extraordinary conditions that have been criticized as improbable, whereas other plausible models may be inapplicable to the Himalaya (see Harrison et al., 1999a; Hodges, 2000 for detailed reviews).

Traditionally, the principal approach to understanding the origin of the apparent inverted geotherm adjacent the MCT and anatexis in its hanging wall was to speculate on the heat sources responsible for creation of these petrologic phenomena and then utilize physical modeling to attempt to simulate the observed geology (e.g., England et al., 1992). An alternative strategy is to establish timing relationships between rocks of the inverted metamorphic sequence, deformed hanging wall, and leucogranite bodies (e.g., Harrison et al., 1997b). Together with thermobarometric data, these results support a model that ascribes the apparent inverted geothermal structure to the juxtaposition of right-way-up metamorphic sequences during the Late Miocene. Thus the longstanding assumption that the MCT was inactive during the post Early Miocene appears deeply flawed.

## 3.2. Kinematic models of MCT evolution

Kinematic models that have been developed to describe the evolution of the MCT are restricted to predicting geometric relationships. The rheological and thermal properties of the rocks involved and the mechanisms responsible for their motion are not considered. Schematic geometric descriptions of the deformed state of these models are shown in Figures 3.1 and 3.2.

### 3.2.1. MCT slip and inverted metamorphism

Figure 3.1 illustrates kinematic models that attempt to describe the relationship between Himalayan inverted metamorphism and MCT slip. For example, Hubbard (1996) proposed the Greater Himalayan Crystallines and Lesser Himalaya were right-way-up metamorphic sequences that were ductilely sheared in a distributed fashion across a broad zone such that the isograds were brought into approximate parallelism with the shear zone boundaries (Figure 3.1a). To explain second order features of the isograd distribution, Hubbard (1996) allowed that frictional heating and/or heat advection via fluid migration may have occurred. Searle and Rex (1989) suggested ductile shearing adjacent the MCT and normal faulting along the STDS created a large-scale fold that aligned pre-existing isograds into an apparent inverted metamorphic sequence (Fig. 3.1b). These models temporally decouple fault slip from the process that resulted in the apparent thermal gradient now observed in the MCT footwall.

Models in Figure 3.1 correlate mineral isograds to structural discontinuities, a process often difficult to ascertain in the Himalaya. Although the recumbent folding model may be appropriate for western Zanskar, similar folded isograds have yet to be found within the Greater Himalayan Crystallines elsewhere in the Himalaya (Hodges, 2000). The main limitation of this class of models is that they suggest that the MCT slip was a single episode, sometimes acting simultaneously with slip on the STDS (e.g., Searle and Rex, 1989). This is contradicted by dates of metamorphic monazite grains collected in central Nepal that indicate the MCT shear zone was active at ~6 Ma (Harrison et al., 1997b) while ductile deformation in the hanging wall was assumed to have termination during the Early Miocene (e.g., Schelling and Arita, 1991).

### 3.2.2. MCT slip and other Himalayan geologic elements

The origin and development of other geologic elements of the Himalaya have also been linked to MCT slip (Fig. 3.2). For example, large-scale thrusting at the MCT has been proposed to occur simultaneously with extension along STDS (e.g., Burchfiel and Royden, 1985; Hodges et al., 1992, 1993). Geophysical data are consistent with the faults that bound the Greater Himalaya Crystallines converging at depth (e.g., Nelson et al., 1996) leaving the possibility the unit extruded as a wedge between the basal MCT and upper STDS.

Field observations suggest that during uplift, the sedimentary cover of the Greater Himalayan Crystallines decoupled in some locales and slumped along the STDS (Fuchs, 1987). In other locations across the range front, the contact between the Tethys Formation and Greater Himalayan Crystallines is preserved (e.g., Manang area, central Nepal; Fuchs et al., 1988). The distinction between wedge-extrusion models (e.g., Hodges et al., 1992) and those advocating post-orogenic collapse of crust thickened by contraction (e.g., Fuchs, 1987), concerns timing of fault movement. In the former category, extensional deformation is coeval with convergence, whereas in the latter, activity on the STDS post-dates movement along the MCT (e.g., Willet, 1999).

Wedge-extrusion models have been used as the framework to suggest that the High Himalayan leucogranites formed via fluid absent-reactions during decompression (Harris et al., 1993; Harris and Massey, 1994; Inger, 1994). In this model, kyanite-bearing schists at the base of Greater Himalayan Crystallines wedge are source materials for the leucogranite bodies (Fig. 3.2b). Anatexis was triggered by tectonic decompression rather than heating. The melts were extracted from their source, migrated through the Greater Himalayan Crystallines, and were emplaced near the STDS. Problems with this model include: the requirement of rapid and large magnitude denudation for the minor effect that decompression has on melting the source compositions, the difficulty of producing multiple anatectic phases via decompression, and lack of definitive timing constraints linking slip with STDS and anatexis (see Harrison et al., 1999a).

A variation of the wedge-extrusion model is advocated by Nelson et al. (1996), who suggests the Greater Himalayan Crystallines is an earlier extruded equivalent of the partially molten Tibetan middle crust (Fig.3.2c). In this case, thrusting results from anatexis, an idea considered by several Himalayan geologists (Bird, 1978; Swapp and Hollister, 1991; Hollister, 1993). Davidson et al. (1997) suggests an inverted thermal structure within the Greater Himalayan Crystallines in Bhutan was produced by thrusting hot migmatitic rocks over lower grade rocks and by the advection of heart from the intrusion of leucogranitic dykes and sills during decompression. Swapp and Hollister (1991) emphasized the role of partially molten crust as a means to localize strain.

To evaluate the feasibility of these models, timing constraints of the history of STDS slip and the generation of leucogranite melts are essential. The available geochronology suggest the STDS was active in the interval of 17-14 Ma, whereas the majority of High Himalayan leucogranites were emplaced 24-19 Ma (see Harrison et al., 1999a). These data tend to support the idea of post-orogenic collapse of crust thickened by contraction, rather than wedge extrusion. Furthermore, the idea that the STDS may be laterally discontinuous (e.g., Fuchs et al., 1988) restricts models that require a significant role for the structure to certain regions of the Himalaya.

## 3.3. Mechanical models of MCT evolution

Mechanical models of MCT evolution are primarily concerned with the response of the thrust and the rocks it separates to applied forces. These are constrained by the laws of mechanics as well as geometry, physical conditions and temporal constraints (Fig. 3.3).

### 3.3.1. MCT slip, inverted metamorphism, and granite formation

Le Fort (1975) proposed that the inverted geotherm was created by the large-scale underthrusting of the cold Lesser Himalaya under a hot Greater Himalayan Crystallines, along with dissipative heating from high shear stress along the MCT (e.g., the hot-iron model; Fig 3.3a). Fluid released from the footwall migrated through the hanging wall where they triggered leucogranite formation in structurally higher levels. This qualitative hypothesis requires simultaneous fault movement, heat generation, and metamorphism.

Simple numerical experiments (e.g., Fig. 3.3b) suggested the hot-iron model of Le Fort (1975) could match Hubbard's (1989) thermobarometric constraints through a combination of heat diffusion and dissipative heating from high shear stress under amphibolite conditions (Molnar and England, 1990, England et al, 1992; England and Molnar, 1993). These quantitative models derive thermal energy from three sources: (1) radioactive nuclides, (2) asthenospheric heat, and (3) frictional heating along the MCT (which is proportional to the shear stress times the slip rate). While some authors emphasize the contributions of (1) and (2) (Bird, 1978; Molnar et al., 1983), more recent contributors find these sources insufficient and require the addition of dissipative heating. Shear stresses >100 MPa can account for peak temperatures in excess of 600°C at the MCT and contribute ~13°C/km to the inverted geotherm (e.g., Molnar and England, 1990) and can induce granite formation if melting occurred after initial slip (see England et al., 1992).

No direct evidence exists that supports such high differential stress *in situ* at plate boundaries (e.g., Zoback et al., 1987; Geist, 1996; Mandal, 1999). Bird (1978) showed that by a simple balance of forces, a nappe stack shortened 20% limits the average shear stress on a 230-km long fault to ≤30 MPa. Modeling of the fault network of Asia using available fault activity, geodesy, and stress information resulted in a shear stress requirement on Himalayan faults of only 15 MPa (Kong and Bird, 1996). Molnar et al. (1983) admit that several parameters are difficult to estimate including: the amount of heat supplied by the base of the lithosphere, the amount and distribution of the radiogenic heat production in the crust, and values of basic parameters (e.g., the thermal conductivity of the crust). At the time the England/Molnar models were formulated, the MCT slip velocity, amount of shortening, timing of footwall recrystallization, and the timing and depth of granite formation were largely unknown.

Royden (1993) suggested the roles of (1) and (2) are the important parameters in an active collision boundary, as well as the processes of subduction, accretion, and erosion (Fig. 3.3c). In the accretion-erosion model, highly radioactive material transfers from an accretionary prism to a hanging wall undergoing rapid erosion. The process is concluded to exert a first-order control on the geothermal structure and anatexis (Huerta et al., 1996, Henry et al., 1997; Huerta et al., 1998, 1999;).

However, accretion-erosion models are inconsistent with the simultaneous emplacement of the High Himalayan leucogranites across the range, as well as their isotopic character (Harrison et al., 1999a). Material transfer from the footwall of the MCT to the hanging wall is required, ignoring the enormous database (e.g., Le Fort, 1996; Parrish and Hodges, 1996; Sharma, 1998; Upreti, 1999; Whittington et al., 1999; Ahmad et al., 2000; DeCelles et al., 2000) that indicates that the thrust marks the boundary between two unique rock packages that are distinguished by detrital zircon ages, isotopic composition, and sedimentary histories.

Wedge-extrusion hypotheses have also been explored as a mechanism to create Himalayan inverted metamorphism and high topography (e.g., Grasemann et al., 1999a, 1999b; Grasemann and Vannay, 1999; Grujic et al., 1999; Grujic and Wosnitza, 1999).

Grujic et al. (1996) suggested southward shearing within the Greater Himalayan Crystallines near and above the MCT and normal faulting across the STDS is explained by a tectonically induced extrusion of a ductily deforming wedge. In this scenario, extrusive flow coupled with heat advection accounts for the apparent inverted geotherm. To test these models, sufficient petrologic, structural, and geochronologic data are required (Grujic et al., 1999).

Harrison et al. (1998) presented a scenario in which the inverted geothermal structure formed by the transposition of several right-way-up metamorphic sequences during Late Miocene slip within the MCT shear zone (Fig. 3.3d). This model used existing thermobarometric conditions estimated for rocks from the Greater Himalayan Crystallines and Lesser Himalaya. By invoking a ramp-flat geometry, it is able to account for the observed lithostatic pressure distribution across the Greater Himalayan Crystallines (e.g., Hodges et al., 1988), as well as the >600°C temperatures at the MCT (e.g., Hubbard, 1989). The widespread appearance of anatexis at middle levels of the Greater Himalayan Crystallines is explained by applying ~20 MPa shear stress along the thrust flat, thereby inducing rocks in these structural positions to partially melt. The model predicts the first appearance of migmatites well above the base of the MCT, as required by field observations. Support for this model comes from monazite Th-Pb ages for samples collected in central Nepal, although the extent that the MCT-reactivation affected other locations across the range remained speculative. Evaluating the Harrison et al. (1998) hypothesis requires additional geochronologic analyses of rocks from similar structural levels along the range front.

### 3.4. Thermobarometric support of models of MCT movement

Models that support the development of a significant inverted geotherm during slip on the MCT require a significantly different P-T path than those that suggest recrystallization of the footwall units occurred prior to their juxtaposition with the hanging wall (Fig. 3.4). For example, in the one-slip hypothesis, a footwall rock follows a P-T path in which it experiences maximum temperature after maximum pressure, due to burial and prolonged exposure to hot hanging wall rocks. The hypothesis that suggests multiple episodes of slip affected the MCT footwall (the multi-slip model) predicts a different metamorphic evolution in which footwall samples experience maximum pressure at the depth of maximum temperature. The sample is buried and quickly exposed to the surface, producing a “hair-pin” P-T path.

Footwall rocks within the multi-slip model should record multiple episodes of burial and exhumation, whereas the single-slip samples only time one stage of fault movement. Younger monazite ages within a footwall rock could be predicted with the single-slip scenario only if enough heat was transferred to warm the rocks to permit daughter product loss. Establishing the metamorphic paths, conditions, and ages from rocks collected from the inverted metamorphic sequence can help to resolve which of the two models may have operated within the Himalayan range.

As illustrated in Chapter 2, the thermobarometric data set for rocks along the Himalayan range is largely restricted to the MCT hanging wall. Because of the lack of thermobarometric constraints from the MCT footwall, some models have resorted to relocating hanging wall P-T data to the footwall. For example, England and Molnar

(1993) model Hubbard's (1989) P-T data without regard to their position relative to the MCT, and conclude the best fit requires a shear stress 250 MPa on a fault dipping 15º at 20 km depth, 4.4 m.y. after initial slip.

### 3.5. Discussion

While their applicability even to the Indo-Asian collision is debated (e.g., Harrison et al., 1999a), numerous models developed to explain Himalaya petrogenesis are routinely exported as paradigms for similar phenomenon in other orogenic belts. For example, Neves et al. (1996) suggests incompletely solidified plutons from the Borborema province of NE Brazil acted as rheological heterogeneities to induce strain localization and shear zone nucleation (à la Hollister, 1993). Decompression melting (à la Harris et al., 1993) has been postulated as a means to form large post-orogenic granite bodies during rapid exhumation of midcrustal granulites in Larsemann Hills, East Antarctica (Carson et al., 1997). Inverted metamorphic gradients in the Monashee complex, southeastern Canadian Cordillera have suggested to form via the downward transfer of heat from an overlying nappe (Parrish, 1995) (à la Le Fort, 1975) or via synmetamorphic ductile inversion of isograds by progressive shear strain (Gibson et al., 1999) (à la Hubbard, 1996). Wedge-extrusion (à la Hodges et al., 1993) has been also been applied to the same area (Johnston et al., 2000). Extension associated with thickened continental lithosphere (à la Dewey, 1988) has even been explored as a possibility to create tessera terrain on Venus (Gilmore et al., 1998).

The evolutionary model of Seeber and Gornitz (1983) is based on traditional rules of thrusting developed over the past 30 years as a means of understanding thrust-belt geometries to inform hydrocarbon exploration strategies, and the forward-propagating sequence of deformation may be oversimplified (see Boyer, 1992; Wells, 1997). At the time of thrust initiation, contractional deformation progresses at the regional scale towards the foreland, but the hinterland of orogenic belts may continue to thicken internally (e.g., Burbank et al., 1992; Attoh et al., 1997; Gray and Mitra, 1999).

In contrast to the above description, Seeber and Gornitz (1983) suggest that the Himalaya is as a wedge of topography between the underthrust Indian plate and overriding Tibet. The active faults include the Main Himalayan Thrust (MHT) and the MCT. Synchronous thrusting and out-of-sequence imbrication are mechanisms in which the topographic wedge (e.g., Davis et al., 1983) maintains a critical taper (e.g., Boyer, 1992). Erosion and accretion of frontal imbricate thrust sheets decrease the thrust-belt taper, which in turn drives internal deformation. Morely (1988) suggests that out-of-sequence thrusts are normal and typical of a contractional deformation sequence, whereas Woodward (1987) suggests that well-dated foreland thrust belts typically display sequential deformation and show evidence of only minor intra-wedge shortening. Models that rely on out-of-sequence thrusts to maintain a critical taper may overlook the requirements of constant wedge strengths and basal sliding laws (Woodward, 1987).

Geochronologic data from the MCT footwall strongly support the idea that the thrust reactivated during the Late Miocene (e.g., Harrison et al., 1997b; 1998). Establishing this event along strike is the primary interest for those seeking to understand the evolution of the Himalaya, and has implications for estimating the amount of convergence accommodated by structures within the range via balanced cross section techniques. Furthermore, it has the potential to establish the idea that out-of-sequence thrusts are usual occurrences in orogenic belts, especially since the Himalaya is considered an ideal natural laboratory the study of continental convergence (e.g., Guillot, 1999; Macfarlane, 1999; Hodges, 2000).